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The report describes the main problems encountered during investigations of the oscillating pressure fields by the Fast Binary Pressure Sensitive Paint (FBPSP). This formulation has response time in the millisecond range and provides compensation of the model displacements and excitation light instability. Measurement methodology, theoretical and experimental estimations of the FBPSP dynamic characteristics are presented. It is shown that FBPSP formulation can be used for oscillation frequencies up to 20-40Hz but requires dynamic compensation of the resulting pressure fields. The experimental results obtained on the pitching wing model at Mach numbers 0.3, 0.4 and oscillation frequencies 0, 5, 10 and 20Hz are presented and discussed.

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Enclosure I

Development and Experimental Investigation of PSP Technique for Pressure Field Measurements on Helicopter Blade

Final Progress Report

by

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Table of Contest

Summary

The report describes the main problems encountered during investigations of the oscillating pressure fields by the Fast Binary Pressure Sensitive Paint (FBPSP). This formulation has response time in the millisecond range and provides compensation of the model displacements and excitation light instability. Measurement methodology, theoretical and experimental estimations of the FBPSP dynamic characteristics are presented. It is shown that FBPSP formulation can be used for oscillation frequencies up to 20-40Hz but requires dynamic compensation of the resulting pressure fields. The experimental results obtained on the pitching wing model at Mach numbers 0.3, 0.4 and oscillation frequencies 0, 5, 10 and 20Hz are presented and discussed.

Introduction

The Pressure Sensitive Paint (PSP) method provides a good opportunity for investigation of unsteady flows. Dynamic parameters of PSP (response time) and measurement system (time, amplitude and spatial resolutions) are determine the ultimate accuracy and should be involved into data processing scheme.

Background

The PSP layer is a two-dimensional array of oxygen sensors, each of them consisting of a polymer binder with the luminophore molecules dissolved in it. The oxygen molecules from the airflow can diffuse into polymer layer. Radiationless energy transfer from the excited luminophore molecules to the oxygen - quenching phenomenon - governs the luminescent output. Quenching of luminescence is controlled by the diffusion of the oxygen inside the polymer binder of PSP. As a result such PSP characteristics as pressure and temperature sensitivity, time response of PSP to the change of external pressure and spatial resolution are diffusion-controlled.

An analysis of these diffusion-controlled characteristics was presented in earlier papers [1, 2 and 4] where it was shown that PSP response in the time domain is determined by oxygen diffusion characteristic time τ (h - paint thickness, D -oxygen diffusion coefficient)

$$\tau = \frac{4 \cdot h^2}{\pi^2 D} \tag{1}$$

and by optical density of the PSP layer d. Theoretical estimations of typical response functions are presented on Fig. 1.

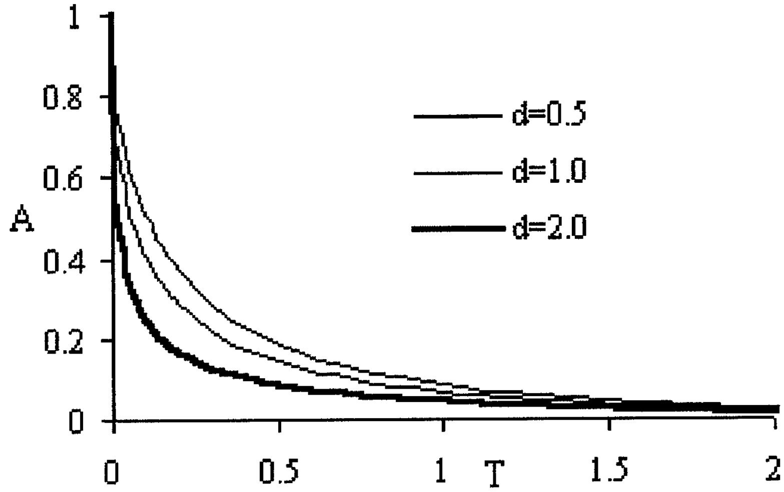


Fig.1. Theoretical estimations of the PSP response function (d-optical density, $T=t/\tau$ -normalized time).

Amplitude-Frequency Characteristics (AFC) and the Phase-Frequency Characteristics (PFC) are presented on Fig.2 and Fig.3 (in these figures $W=2\omega h^2/D = \omega \tau \pi^2/2$)

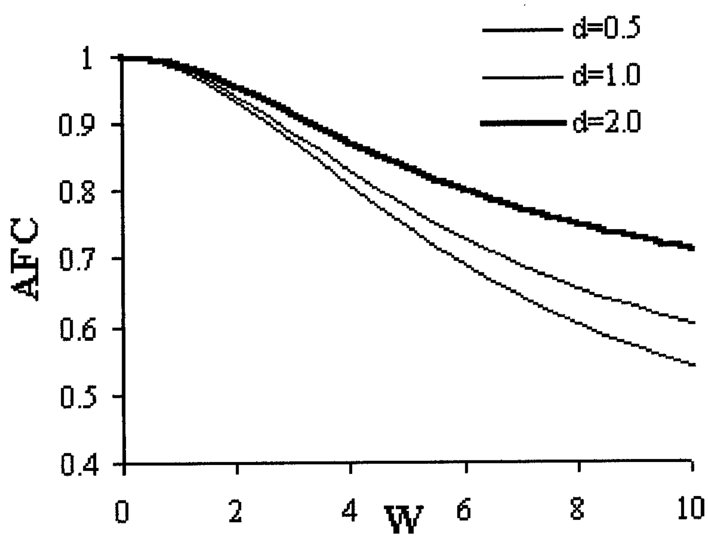


Fig.2. Amplitude-Frequency Characteristic of PSP (d - optical density, W - normalized frequency).

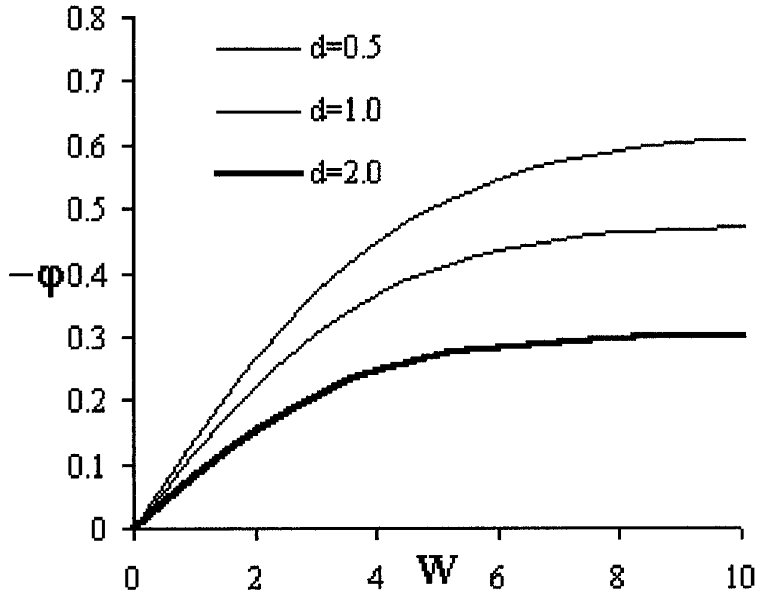


Fig.3. Phase-Frequency Characteristic of PSP
(*d*-optical density, *W*-normalized frequency).

Fast Binary Paint Formulation

The standard approach to compensate the excitation light fluctuation and the model displacements is to use second reference luminophore, which is insensitive to the pressure and having luminescent output in the another spectral range relative to that of the active luminophore [4]. Direct measurements of the PSP response time show that response time in the range of 2-10*msec* can be achieved for the paint layer having thickness about 2-6μm. Such small thickness creates difficulties in implantation of the reference luminophore in the active layer. Usually the reference luminophore is a phosphor crystal grains having dimensions about 5μm that creates significant roughness of the active layer in the case of the direct implantation of phosphor into thin active layer of fast PSP. On the other hand it is impossible to solve two luminophores in the active layer in the necessary quite high concentrations without quite essential cross-influence of this luminophores. The possible solution is to use additional polymer layer binding the reference luminophore as a substrate of the active layer.

Luminescence spectra of luminophores are quite wide so it is impossible to separate them absolutely. It means that calibration parameters will be a function of the spatial distribution of the paint thickness. Plots presented on Fig.4 and 5 shows that PSP calibration parameters in this case are the functions of the relative luminescent output of reference (R) and active (B) components. Temperature sensitivities of the reference and active components have the same sign that results in some temperature self-compensation in the normalized signal.

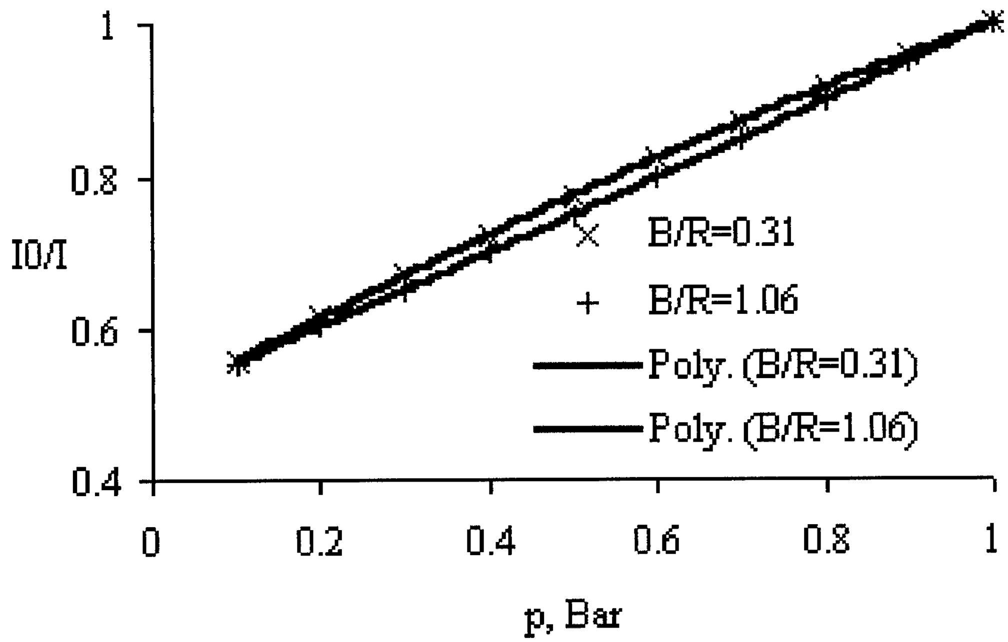


Fig.4. Calibration characteristics of Binary Fast PSP.

Laboratory setup for investigation of PSP response to the step pressure change was described in [4] (Fig.6). A cellulose membrane closed the topside of the tube cell and an air was evacuated from the cell. A needle destroyed the membrane and movement of a shock wave inside the tube was initiated. The pressure relaxation time in the cell was estimated in a range of 50÷200*μsec*, while some sonic waves could also appear in this cell with the main frequency about of 2000*Hz* that was determined by the length of the tube. A continuous luminescent UV lamp performed the excitation of the PSP sample. A photomultiplier tube acquired the luminescence intensity and its output signal was digitized.

Fig.7 presents the time response of the PSP to the step pressure change. This response corresponds to the theoretical predictions with characteristic time τ=2.6*msec*. The response time of 99% relaxation of luminescence intensity is equal to 6.5*msec*. AFC of this PSP is equal to 0.99 at frequency 7*Hz* and 0.7 at 70*Hz*, thus this PSP can be used for unsteady pressure measurements at the frequency up to few dozens of Herz. Some samples of very thin PSP type F2 was prepared and tested in this cell. Their characteristic times were of the order of 100÷300*μsec*.

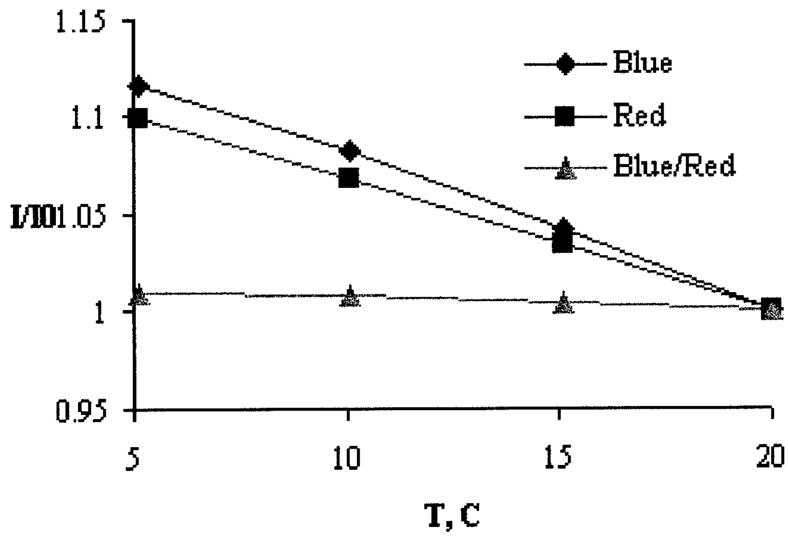


Fig.5. Temperature sensitivity of Binary Fast PSP.

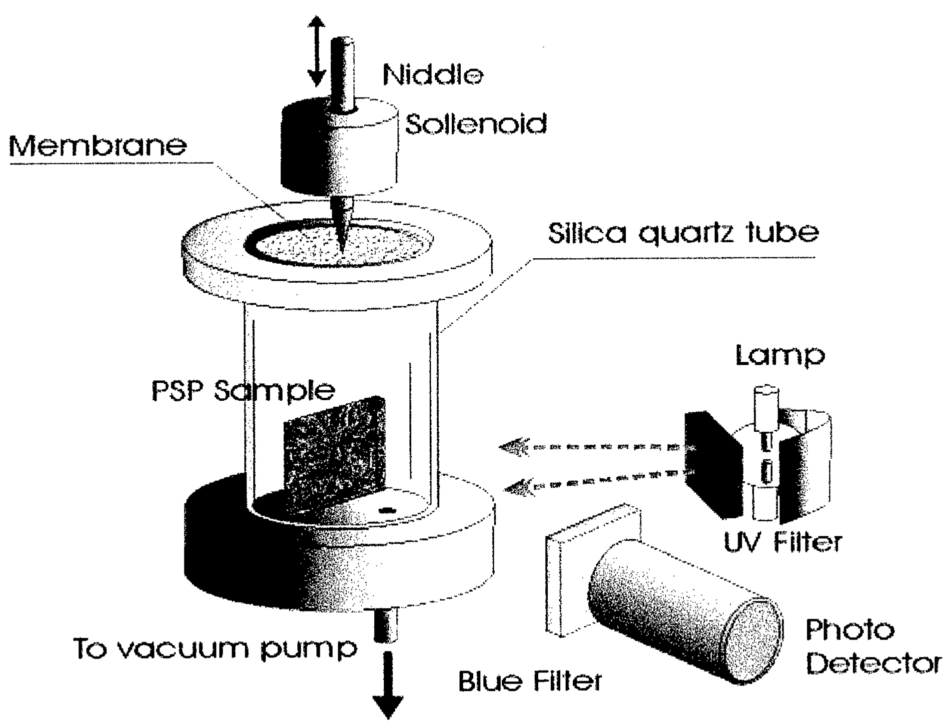


Fig.6. Schematic of a cell for investigation of PSP response to the step pressure change.

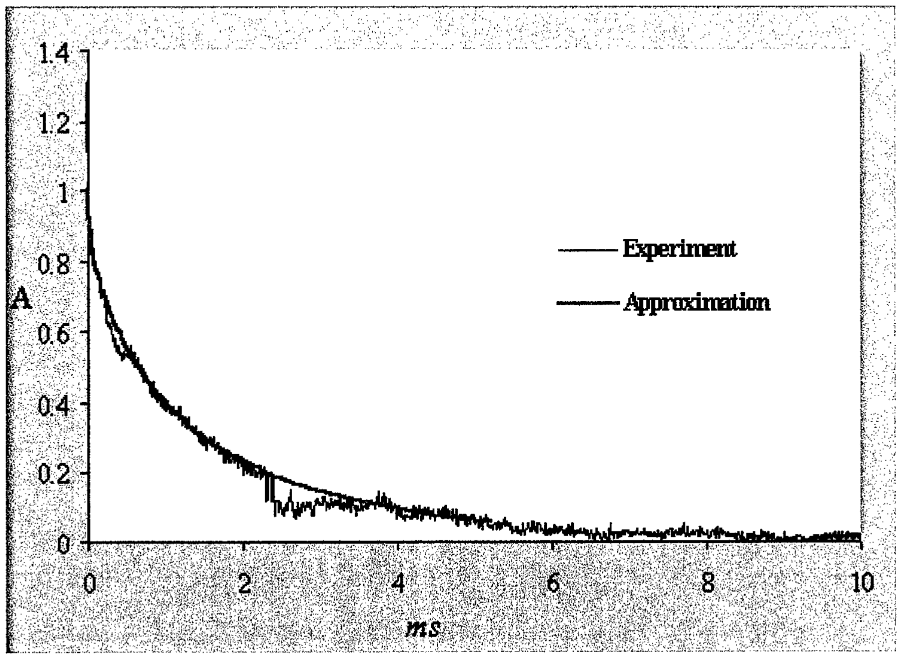


Fig.7. Time response of PSP F2 to the step pressure change, τ=2.6*msec*.

Experimental Setup and Data Processing

The tests was conducted in NASA Ames ARC. A test setup assembled in the NASA Ames wind tunnel to fulfill PSP measurements on an oscillating model is presented in Fig.8. The wing model has NACA0012 profile with 6-inch chord and 5% relative thickness. The pitching harmonic oscillations were created by an actuator mechanism, which provides oscillation frequency from 0 to 20*Hz* with pitching amplitude up to 10°. A pulsed light source was used for PSP excitation at certain phases of the model position. Flash duration of 1*msec* was enough for measurements at the models oscillating frequencies up to 20÷30*Hz*. Two digital CCD cameras with appropriate filters acquired the pressure sensitive and reference luminescence intensities. At the beginning the total lower surface of the model was painted by fast binary paint. Applied active layer was very thin - by estimation the thickness was about 2μm. Unfortunately after model installation in the test section their surface was accidentally sponged down. This procedure resulted in partial removal of the active layer. Finally, only the central section of the model (see "Blue" images in Fig.9) was recovered by active layer that created significant non-uniformity in the layer thickness especially near the model leading edge.

Data processing scheme is presented in Fig.9. During each image acquisition cycle flash lamp was ignited at a predetermined angle of attack and two images were acquired using separate CCD cameras with appropriate glass filters. Reference images were acquired at the same angle of attack without flow. After image alignment procedure the C_p fields were calculated and these fields were transferred to the net model of the wing section. Special markers were applied to the model surface for the image alignment and resection. For several model positions resection procedure was conducted in the interactive mode. Data processing was performed with 'OMS' software developed in TsAGI.

Dynamic compensation of the local PSP response time was implemented in the data processing. Paint thickness distribution was estimated from development of the two additional images: "white screen" - intensity distribution from the model surface covered by white paper, and standard "blue" image for the same angular position of the model. As soon as these images were acquired in different time it was necessary to average the set of them to minimize spatial instability of the light source. After alignment and normalizing the resulted image was transferred on the net and this image was used for estimation of the spatial AFC&PFC fields of the active layer. The sets of the resected images for each oscillation frequency were harmonically approximated up to the 4^{th} harmonic. The sufficiency of four harmonic approximations is clearly observed in Fig.10 where distribution of harmonic amplitudes are presented for F=0Hz and F=20Hz.

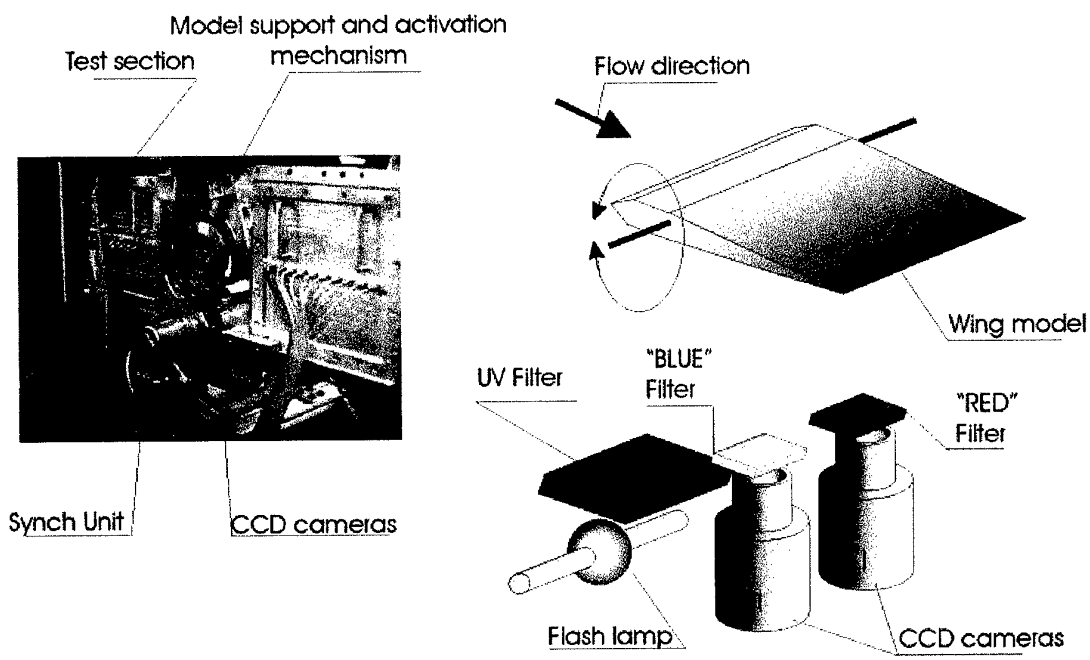


Fig.8 Schematics of the test setup for PSP measurements on the oscillating model.

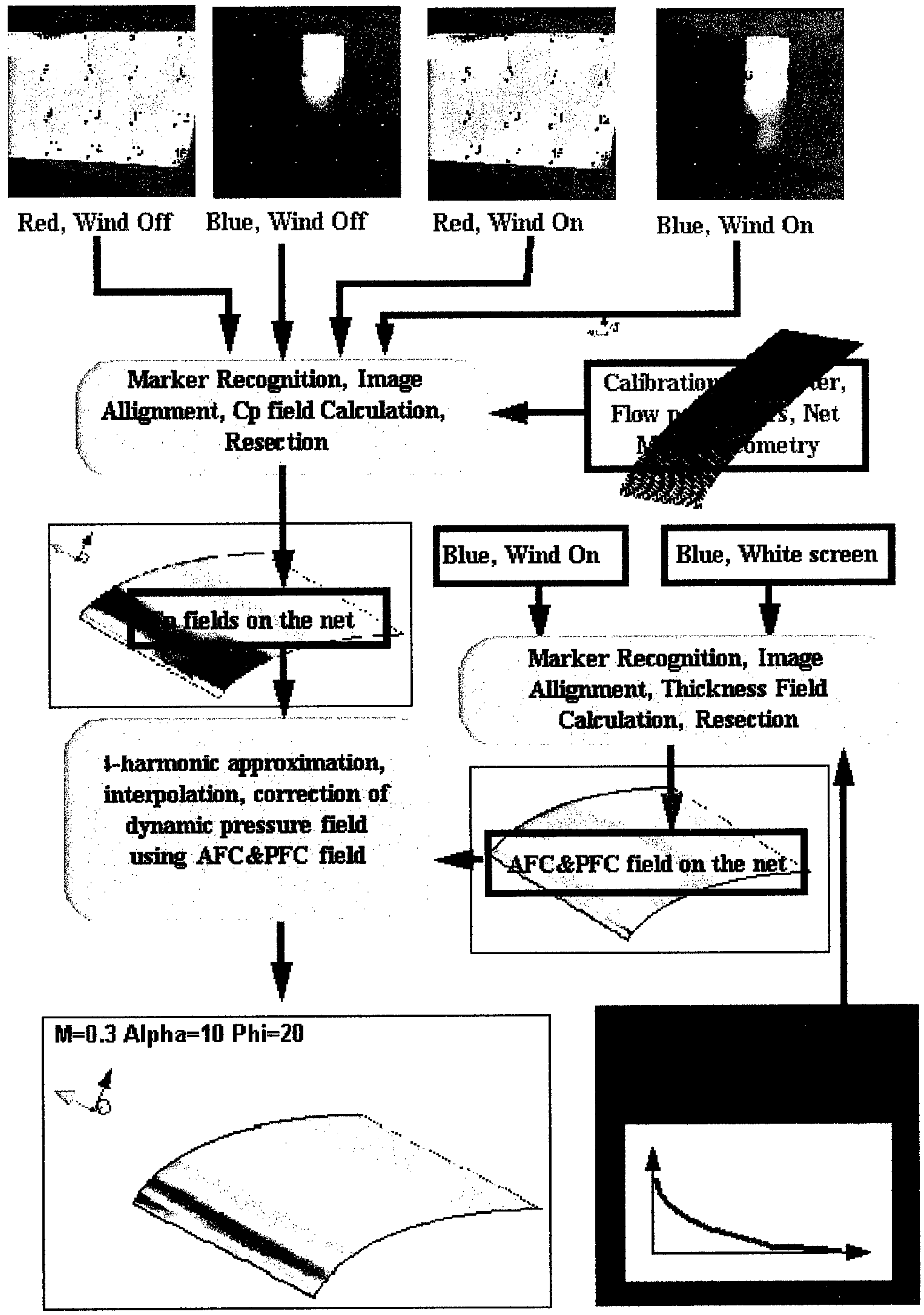


Fig.9. Data Processing Scheme.

Second harmonic amplitude is about 10% of the first one even for steady case, for F=20*Hz* second harmonic is significantly attenuated by paint response - attenuation factor is about 5-7. Third harmonic amplitudes are in the measurement accuracy area for both cases.

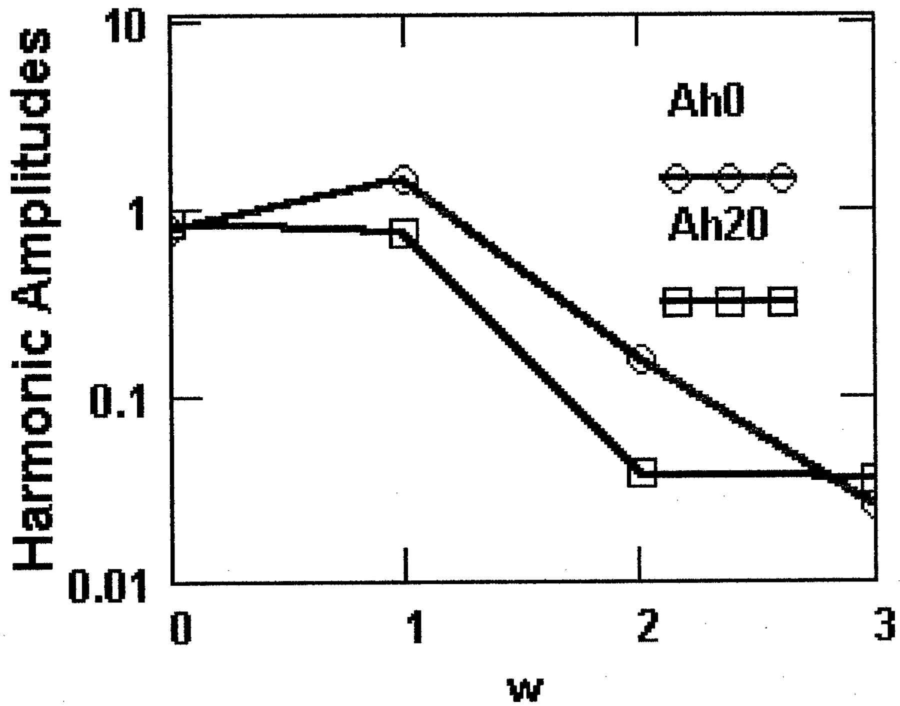


Fig.10. Harmonic amplitudes distributions for F=0*Hz* (Ah0) and F=20*Hz* (Ah20), M=0.3 (w-harmonic number, region x=0.16 in centerline section).

This information was enough for dynamic compensation but this is very time consuming operation for the total set of the pressure fields. Thus dynamic compensation procedure was mainly applied for pressure distributions in the model centerline section and only for the few cases for the total fields.

Pressure field investigations on the pitching model

The Program was performed in the subsonic wind tunnel of NASA Ames ARC. Measurements were conducted at oscillation frequencies 0, 5, 10 and 20*Hz* and a flow Mach numbers 0.3 and 0.45. Image information was acquired for angles of attack from -10° to +10° with 2° step.

Plots in Fig.11 demonstrate C_p distributions along wing centerline for angle of attack 8°, M=0.45 (F=0, 5, 10, 20*Hz*). Variation of the amplitude damping and phase delay for different oscillation frequencies shows that dynamic response parameters of the paint active layer significantly disturbs registered pressure fields. It is clearly observed in pressure fields especially for high positive angle of attack. Significant 2D pressure distribution near leading

edge, which is absent for steady environment, can not be attributed due to some transient flow effect.

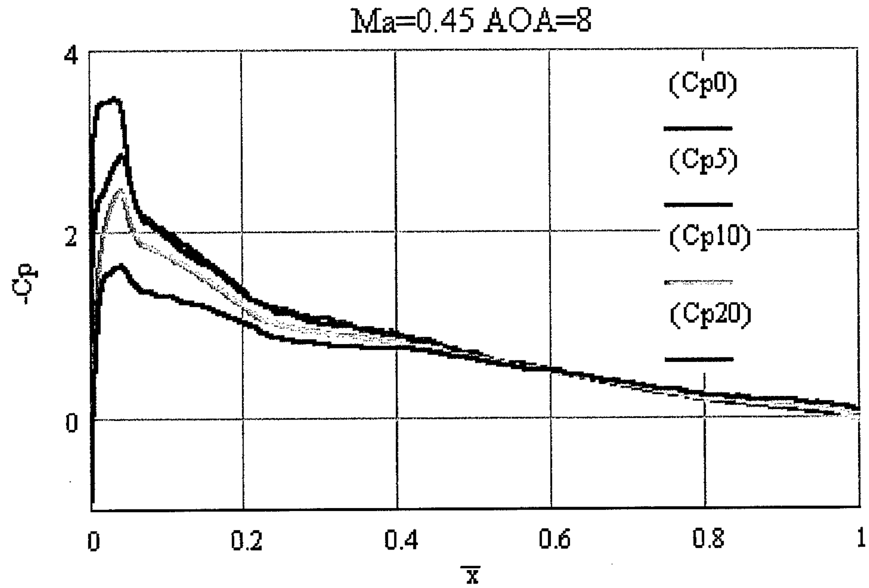


Fig.11. Pressure (Cp) distributions in the centerline section for oscillation frequencies 0*Hz* (Cp0), 5*Hz* (Cp5), 10*Hz* (Cp10), 20*Hz* (Cp20) Mach number 0.45 and angle of attack 8°.

Plots in Fig.12 show C_p distributions along a wing chord for +10° and -10° angles of attack, M=0.3 for oscillation frequency F=20*Hz* and F=0*Hz* (static environment).

The response time of the PSP sample applied simultaneously with PSP application on the model surface was measured after experiment in laboratory on the setup described above and was found is 6*msec*. This response time corresponds to a cutoff frequency of 30*Hz*, which means that for the model oscillation frequency of 30*Hz* this paint realization can resolve only several harmonics and actual AFC&PFC characteristics of the paint should be taken into consideration. This model was not equipped with a conventional pressure measurement system but pressure distributions obtained for zero frequency are in a good agreement with the pressure distributions for this profile type and results obtained by CFD panel method. Such calculations were performed for steady state environment (F=0*Hz*) and comparisons are presented in Fig.13, 14.

As mentioned above PSP response time is a function of the paint thickness. Paint thickness distribution can be estimated by a luminescent output distribution normalized on an excitation light distribution. This distribution for centerline of the painted strip is presented on Fig.15.

Resulting AFC and PFC distributions for 20*Hz* frequency and higher 2nd and 3rd harmonics are shown on Fig.16 and 17. These estimations can be used for dynamic compensation of the measured pressure distribution as its shown on Fig.18 and 19 for the first harmonic of the C_p distribution obtained for M=0.3 and oscillation frequency 20*Hz*.

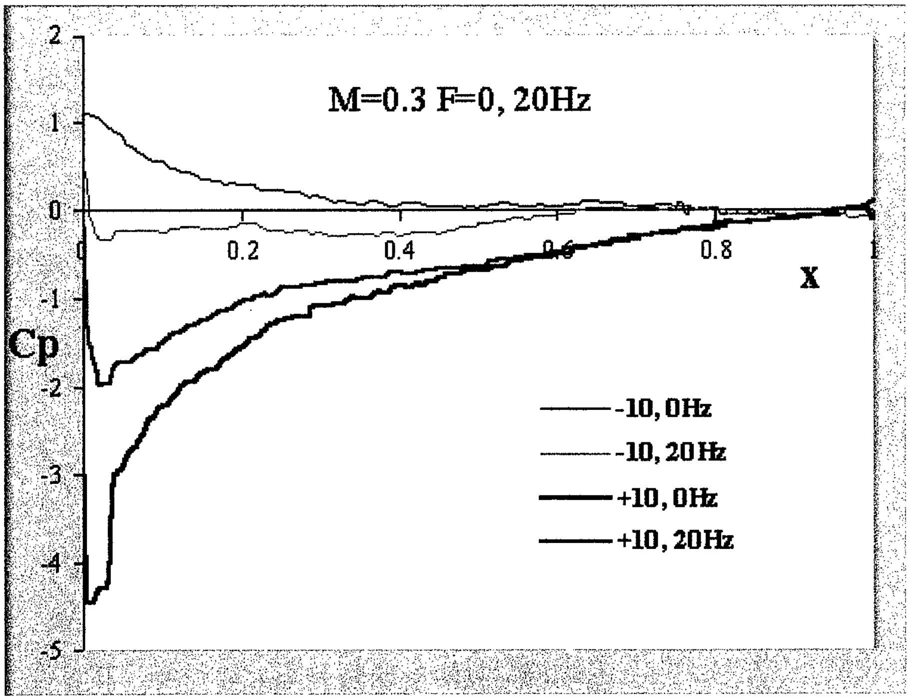


Fig.12. C_p distributions (x -normalized coordinates along the wing chord).

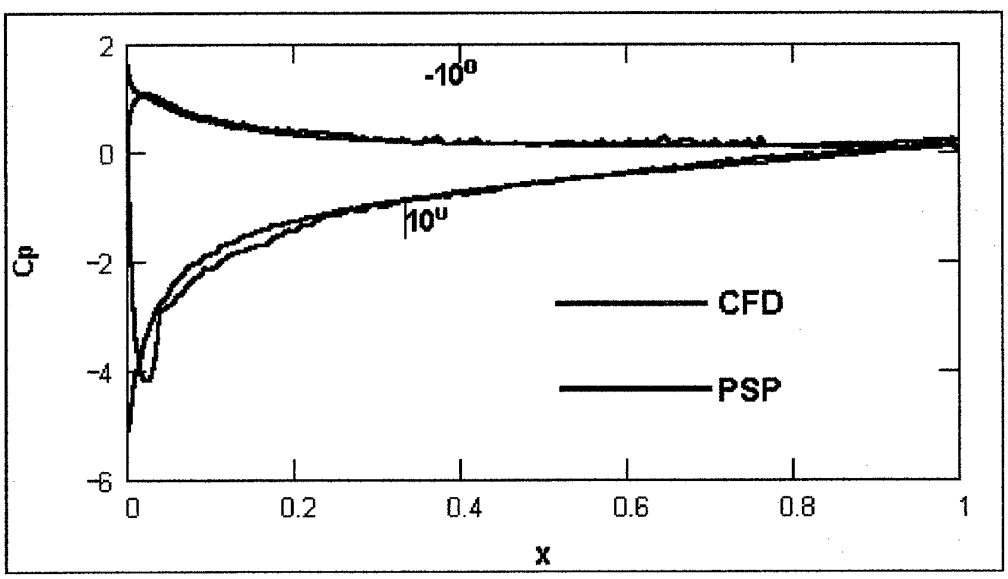


Fig.13. PSP-CFD comparison for centerline section, M=0.3, F=0Hz.

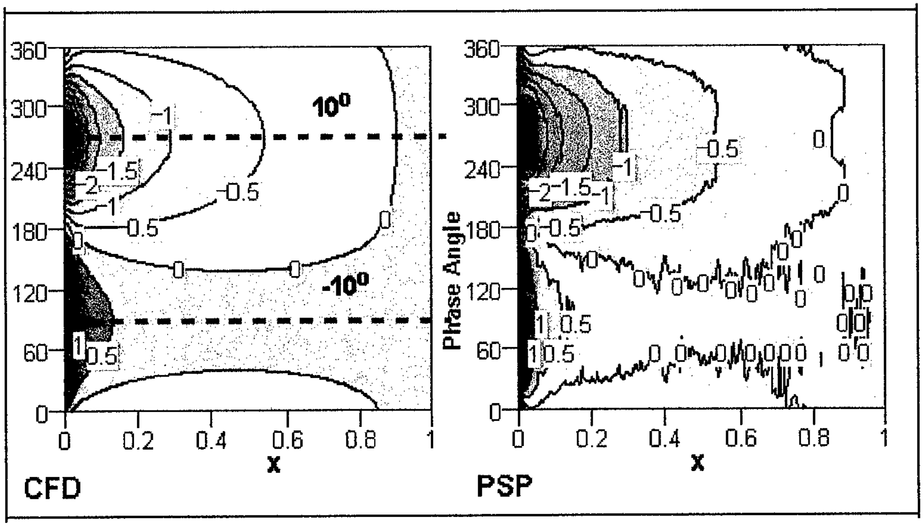
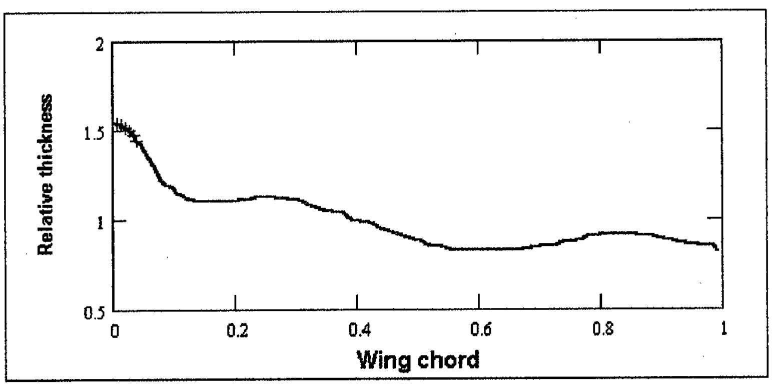
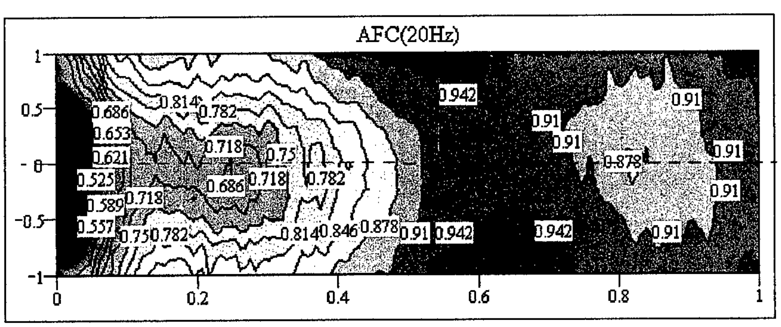


Fig.14. Phase image of C_p evolution in the model centerline section obtained by CFD and PSP, M=0.3, F=0Hz
(Dotted blue lines correspond data presented in Fig.13).



Relative thickness of the active layer along the wing centerline



Amplitude Frequency Characteristic of the active layer for F=20Hz

Fig.15. Estimation of the active layer thickness in centerline section and estimation of the AFC field for F=20Hz.

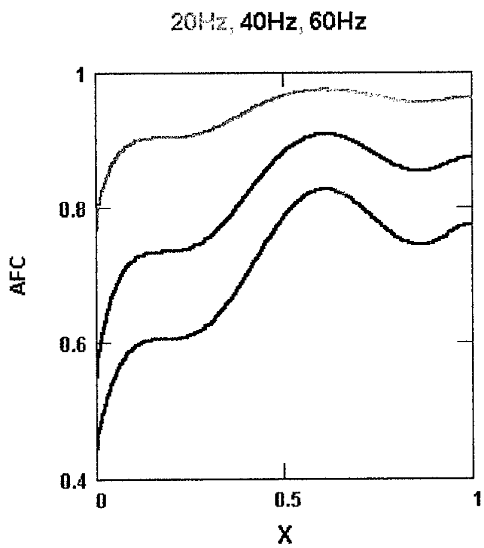


Fig.16. AFC distributions for the first three harmonics.

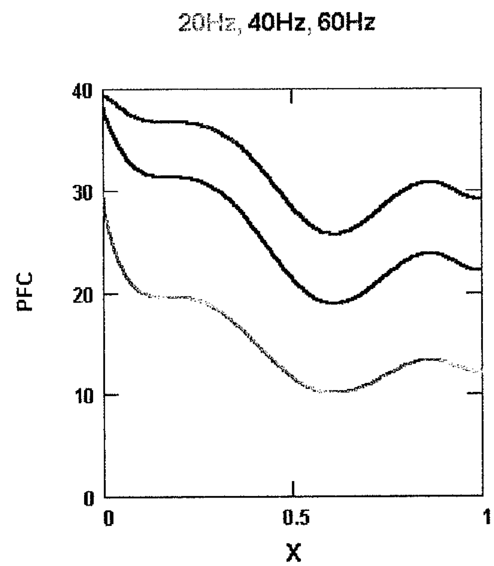


Fig.17. Phase delay distributions (-PFC) for the first three harmonics.

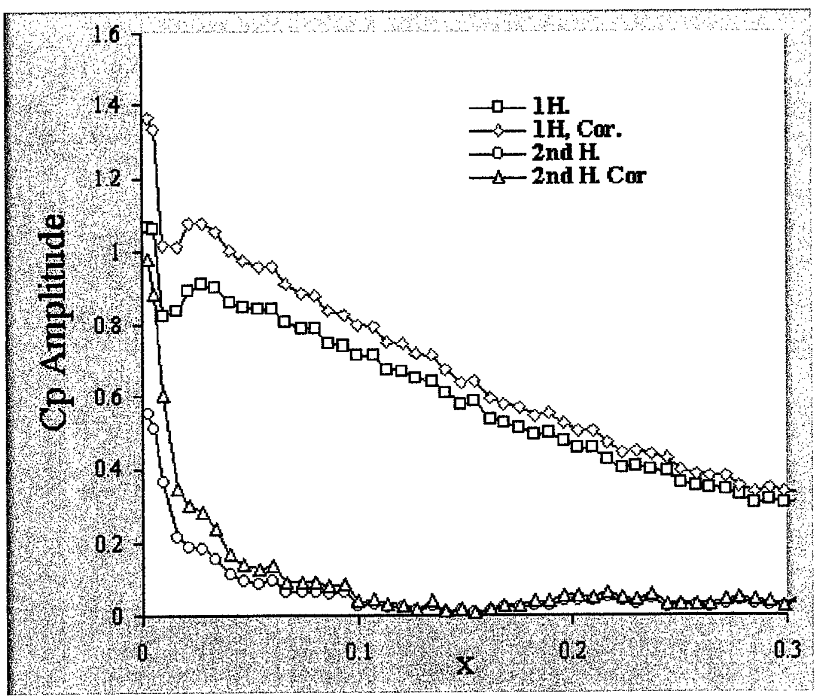


Fig.18. C_p amplitude corrections for 1st and 2nd harmonics.

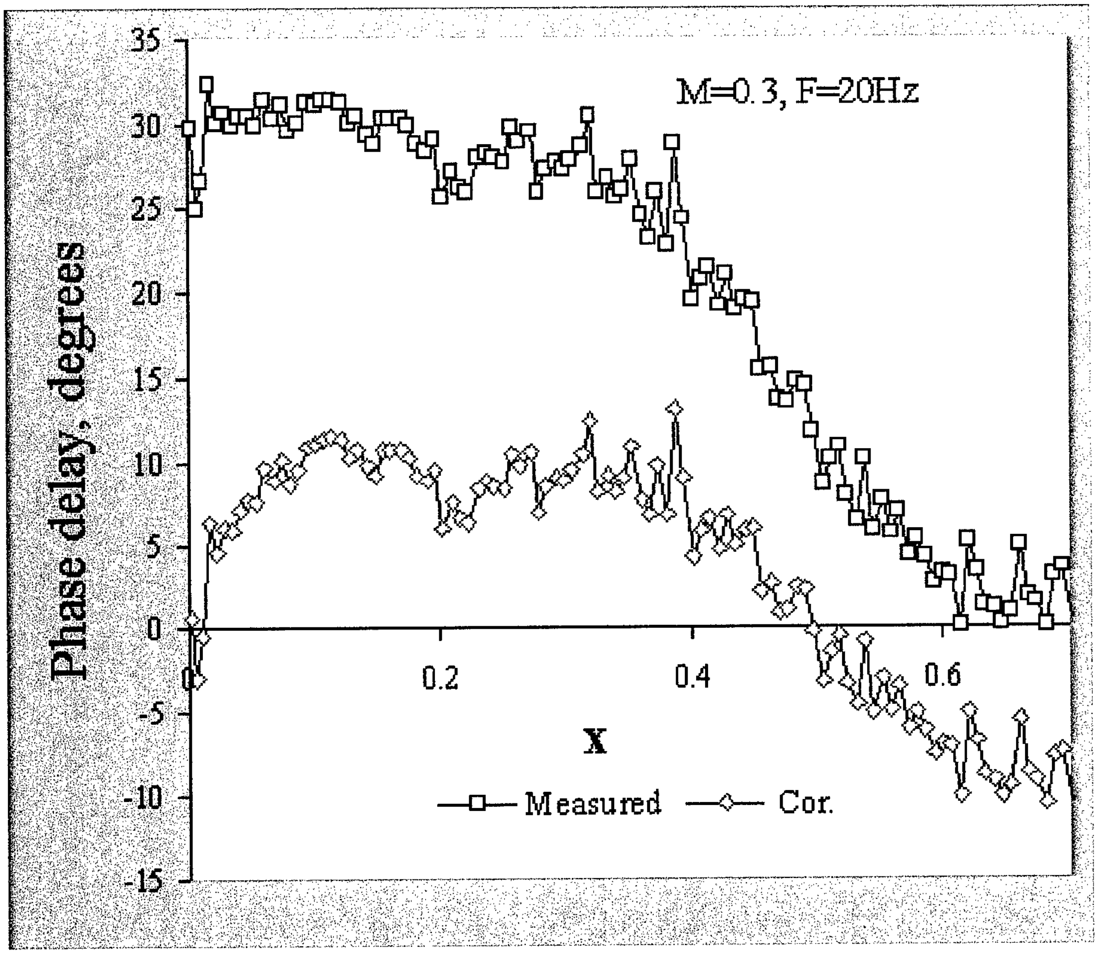


Fig.19. Phase Delay Correction for the 1st harmonic.

Corrected phase delay distribution crosses zero axis at x coordinate 0.5 corresponding model oscillation axis, average phase delay near leading edge is about $\delta\phi_{psp}$=5-7°. These values can be meaningful for oscillation frequency F=20Hz, half wing chord a=76mm and flow velocity V=100m/sec giving an estimation for the phase lag $\delta\phi_{est}= 2\pi \times F \times a/V \cong 5.4°$.

Results presented in Fig.20 and 21 show that the initial pressure gradient along wing span was removed after dynamic correction.

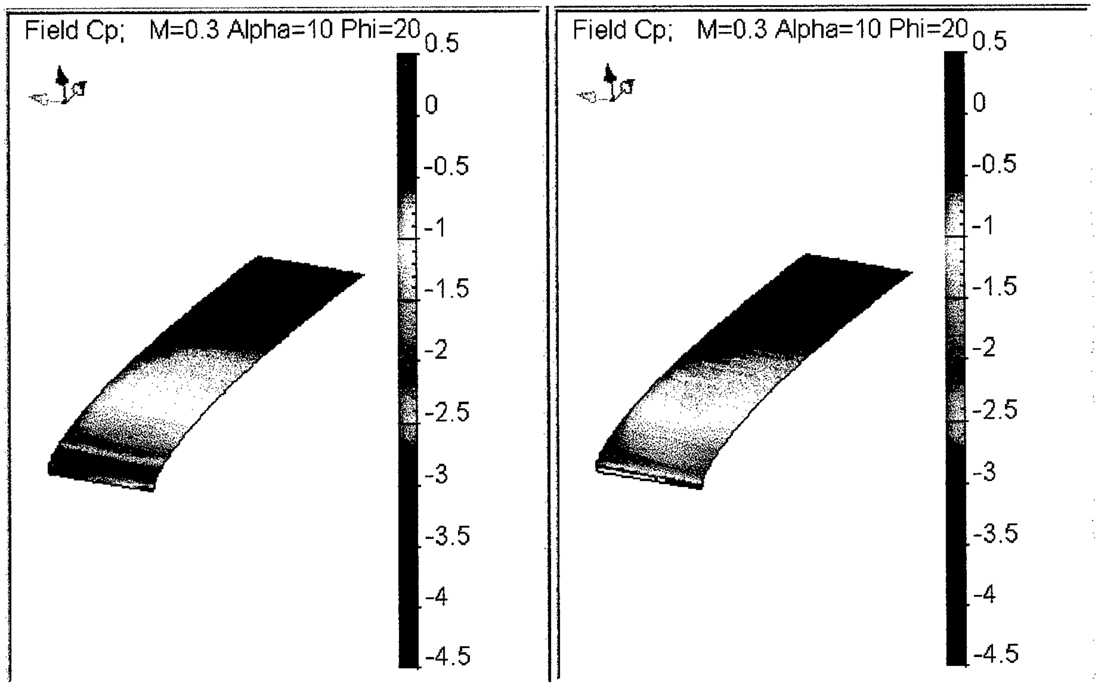
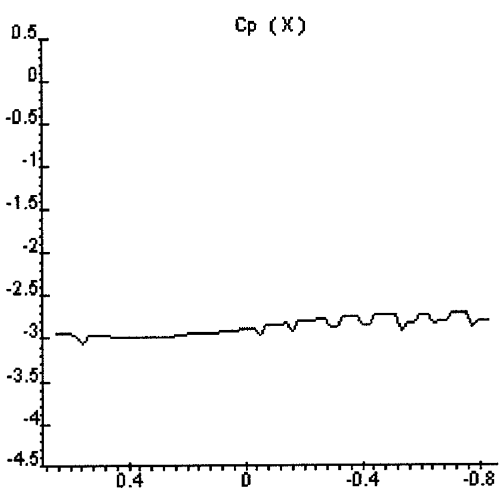
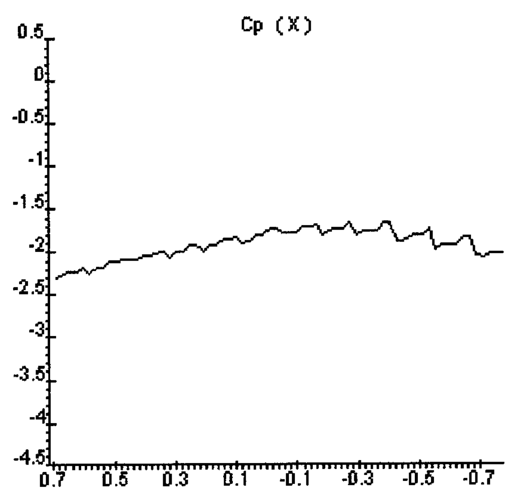


Fig.20. C_p distributions for M=0.3, F=20Hz, corrected -left and source, non-corrected - right.



Corrected Cp distribution along wing span, section x=0.22, M=0.3, AOA=10°



Non-corrected Cp distribution along wing span, section x=0.22 M=0.3, AOA=10°

Fig.21. Correction of results.

Plots in Fig.22 and 23 demonstrate that at high angle of attack there is still discrepancy between corrected PSP results for F=20Hz and for F=0Hz. This discrepancy can be attributed as due to real dynamic effect in flow behavior as well as due to some error in determination of the actual AFC&PFC characteristics.

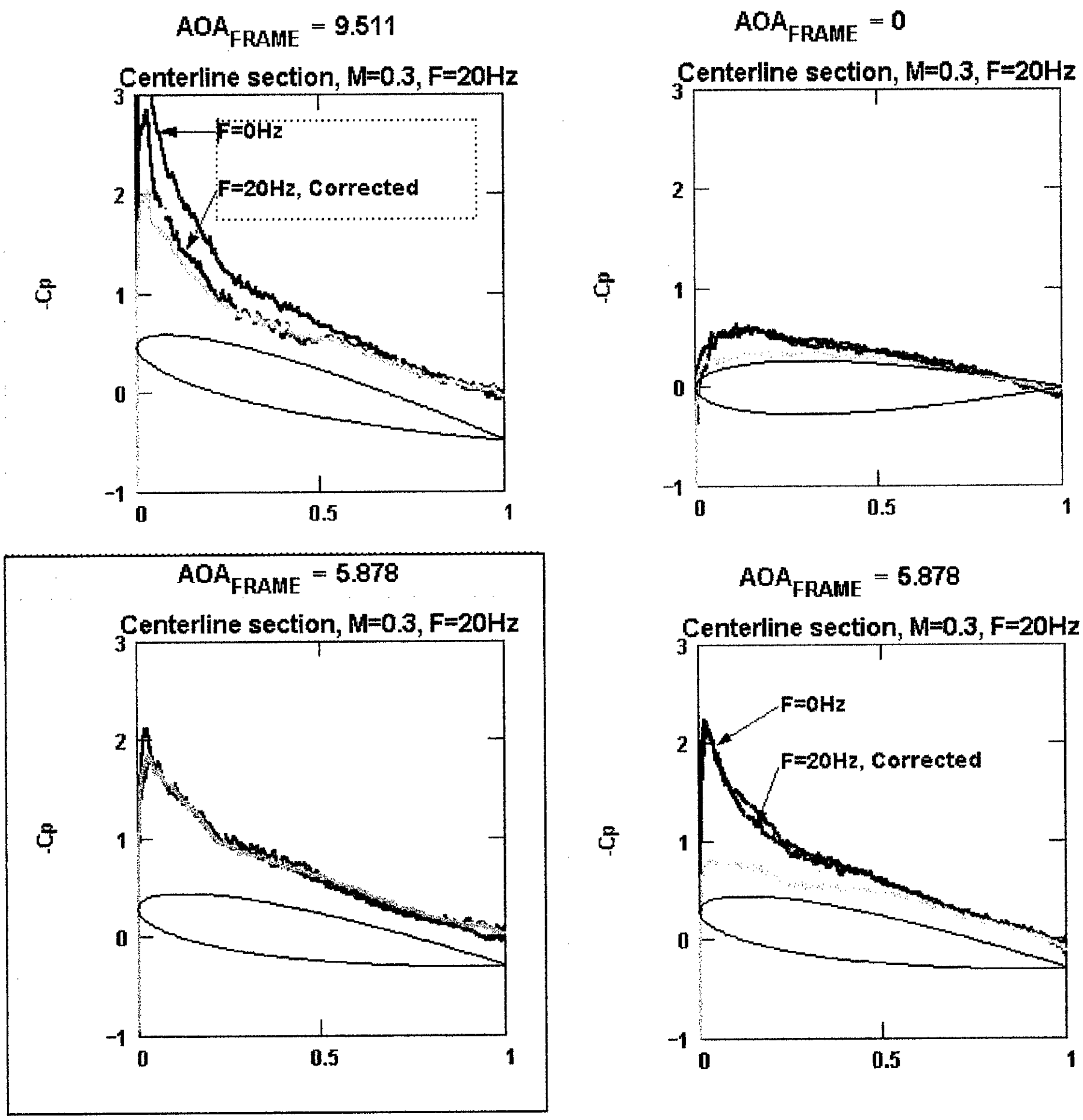
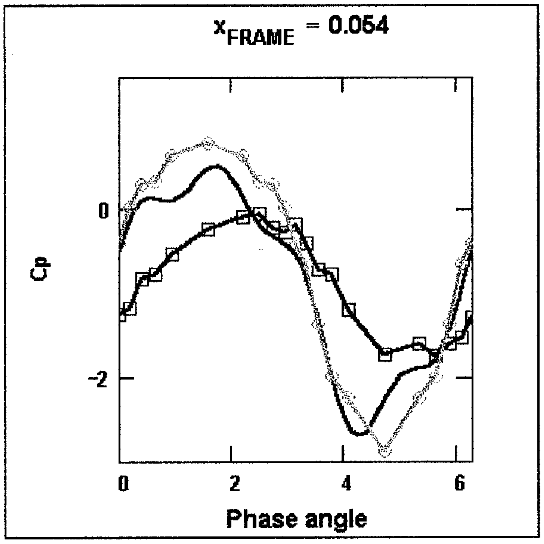


Fig.22. Comparison of the C_p distributions for F=0Hz and F=20Hz (corrected and source) M=0.3.



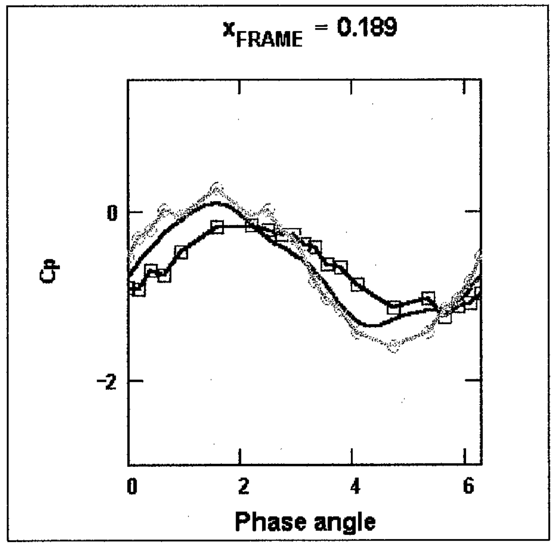


Fig.23. C_p behavior as function of the phase angle for centerline points in section x=0.054 and x=0.189 for M=0.3:
F=0Hz - green line, F=20Hz, source - blue line, F=20Hz, corrected - red line.

Conclusion

Theoretical estimations and experimental research show that binary fast PSP can be used for pressure field investigations on the oscillating models at frequencies up 20-40Hz. Taking into consideration of the dynamic parameters of the paint can increase the measurement adequacy. Binary composition compensates the influence of the model movement and excitation light instability.

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Publications

◊ S.D. Fonov, R.H. Engler, Chr. Klein, S.V. Mihailov, V.E. Mosharov, V.P. Kulesh, V.N. Radchenko, E. Schairer, "Investigations of the pressure fields on the oscillating wings by Pressure Sensitive Paint." DGLR-Fach-Symposium der AG STAB, Technischen Universitat Berlin, November 10-12, 1998.

◊ S.D. Fonov, R.H. Engler, Chr. Klein, S.V. Mihailov, V.E. Mosharov, V.P. Kulesh, V.N. Radchenko, E. Schairer, "Pressure Sensitive Paint for Oscillating Pressure Fields Measurements." In ICIASF'99 Record, Toulouse, France, 1999.

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